Atmospheric muons and neutrinos from charm*

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We have updated our previous investigation of the production of muons and neutrinos in cosmic ray interactions with the atmosphere, taking account of recent results from the *ep* collider HERA in our QCD-based model for hadronic interactions. Qualitatively, our previous results remain unmodified: our predictions for the conventional muon and neutrino fluxes agree with earlier calculations, whereas the charm particle treatment we use gives significantly lower prompt fluxes compared to earlier estimates. This implies better prospects for detecting very high energy neutrinos from cosmic sources.

The flux of muons and neutrinos at the Earth has an important contribution from decays of particles produced through the interaction of cosmic rays in the atmosphere. This has an interest in its own right, since it reflects primary interactions at energies that can by far exceed the highest available accelerator energies. It is also a background in studies of neutrinos from cosmic sources as attempted in large neutrino telescopes.

We have updated our detailed study of muon and neutrino production in cosmic ray interactions with nuclei in the atmosphere [1,2] by taking into account the information on nucleon structure functions from recent experiments at the *ep* collider HERA [3,4] and by refining our simulation of particle cascades in the atmosphere with a better treatment of secondary particles. A complete description is presented in ref. [5].

Our investigations agree with earlier studies on the fluxes of atmospheric muons and neutrinos coming from decays of π and K mesons. On the other hand, we find quite low fluxes for prompt muons and neutrinos, which arise through semi-leptonic decays of hadrons containing heavy quarks (most notably charm). Other estimates of these prompt fluxes [6–11] are higher than ours, and vary by few orders of magnitude. These differences come from extrapolating charm production data from accelerator energies to the orders-of-magnitude higher energies of the relevant cosmic ray collisions. Current data from surface and underground detectors attempting to measure the flux of prompt muons and neutrinos (see *e.g.* [12]) are still too discrepant to discriminate between the different models for charm production.

The main contribution of our study is in using proper charm production data and a sound physical model based on QCD. First, we use recent charm cross section measurements that form a consistent set of data, but disagree with some of the early measurements that were substantially higher. Secondly, we apply state-of-the-art models to simulate charm particle production in high energy hadron-hadron interactions.

We have obtained the atmospheric muon and neutrino fluxes with two different methods: via a Monte Carlo simulation of the hadronic cascade and via approximate analytical expressions with energy-dependent Z-moments. We were satisfied that the two methods, which are conceptually rather different, gave quite similar results. Differences were typically less than 20%, below the uncertainty in our charm calculation and quite acceptable in this context.

Very different prompt fluxes are predicted by

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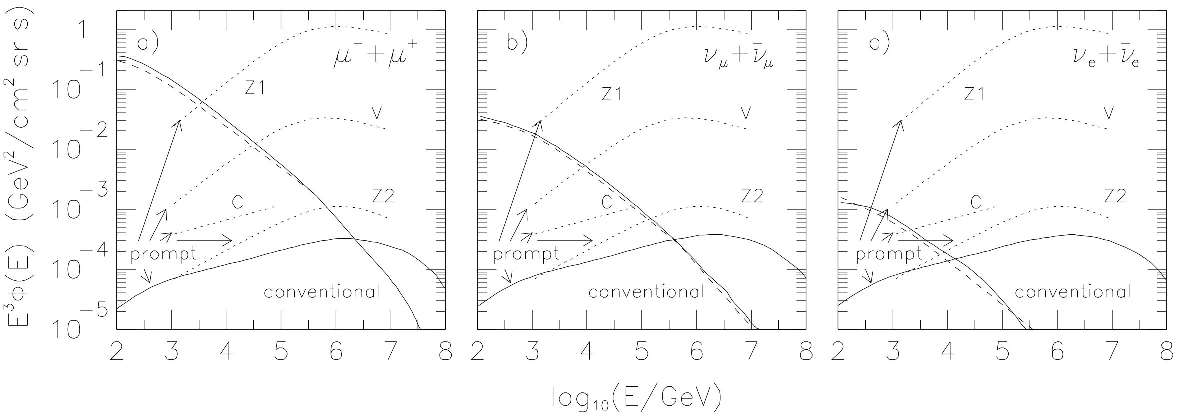

Figure 1. Our prompt and conventional muon and neutrino fluxes (solid lines) compared with those in other models for charm production.

other models for charm production, which differ both in the magnitude and energy dependence of the total charm production cross section and in the distribution in longitudinal momentum fraction of the charmed particles.

Volkova *et al.* [6], applying the so-called ‘quark-gluon string model’ [13], obtained the curves labeled V in fig. 1. Castagnoli *et al.* [7] obtained the result marked C. Both models use a parametrized energy dependent charm cross section (curves C and V respectively in fig. 2) normalized to early experimental data which are substantially above later measurements. A more recent calculation based on the QGSM by Gonzalez-Garcia *et al.* [8] gives fluxes that are comparable to curve C in fig. 1.

Curves marked Z1 and Z2 in figs. 1 and 2 are from Zas *et al.* [9]. Curves Z1 illustrate an extreme model where the charm cross section is simply taken as 10% of the total inelastic cross section (which is curve $\sigma^{\rm tot}$ in fig. 2). This is substantially higher than all charm data. Curves Z2 correspond to charm *quark* production calculated with leading order perturbative QCD matrix elements using relatively hard parton distributions.

All the previous models except Z2 assume Feynman scaling for the charm energy spectra. Bugaev *et al.* [10] considered Feynman scaling violations through a phenomenological equation. Their calculation resulted in overall prompt fluxes slightly lower than Volkova’s (curve V). Their fluxes are higher in the non-scaling case than in the scaling case (opposite to our results).

Our model (solid lines in fig. 1 and curve MC in fig. 2) uses leading order perturbative QCD matrix elements supplemented by a correction $K = 2$ for next-to-leading order processes. It incorporates a strong breaking of Feynman scaling, arising from the dominance of perturbative charm quark production close to the charm threshold. For the parton densities in the nucleon we have adopted the $MRS\,G$ parametrization [14], which uses essentially all relevant experimental data, from deep inelastic scattering experiments to recent results from the *ep* collider HERA [3,4]. Actually, since a naive extrapolation of the G parametrization below the measured region in x at rather small $Q^2 \sim m_c^2$ leads to a presumably unphysically large charm production cross section, we have implemented a flatter dependence as $x \to 0$ like $x^{-\epsilon}$ with $\epsilon \simeq 0.08$ (cfr. [15]). Curves labeled G and D_0 in fig. 2 show the charm production cross section one would obtain from the (unflattened) G parametrization and from the now-unacceptable $MRS\,D_0$ parametrization [16].

Some of the previous models give charm pro-

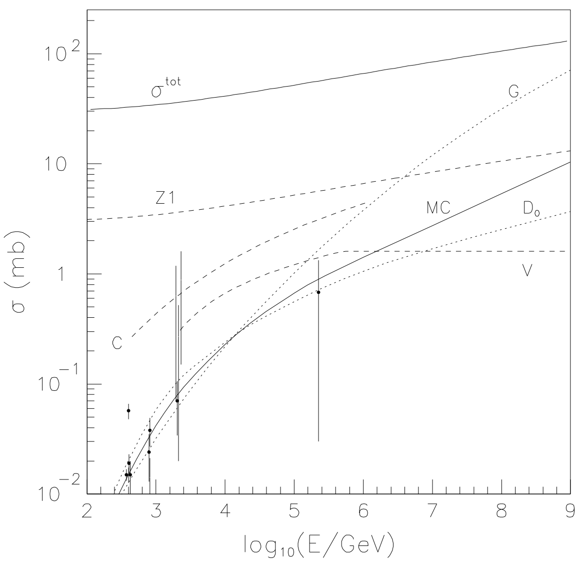

Figure 2. Energy dependence of charm production cross section in pp ($p\bar{p}$) collisions. References to experimental points are given in ref. [5]. Curves are described in the text.

duction cross sections higher than recent data (see fig. 2) and some assume Feynman scaling for the longitudinal momentum distributions. In some cases one may have been mislead in the construction of the models by the early charm measurements that turned out to be substantially higher than the measurements done later. Our model instead gives a fair description of measured charm production cross sections and applies well-motivated charm particle momentum distributions with significant Feynman scaling violations.

With respect to other models for charm production, we predict substantially lower muon and neutrino atmospheric fluxes from decays of charm mesons. In particular, we predict an interestingly low prompt neutrino background to searching high energy neutrino cosmic sources in large scale neutrino telescopes.

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